Mathematical Capture of Human Crowd Behavioral Data for Computational Model Building, Verification, and Validation

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ABSTRACT: *This paper describes the Army-funded exploratory work in progress at the Target Behavioral Response Laboratory. Crowd behavior data collected under controlled laboratory conditions form the basis for mathematical models of human behavior, which are then coded into computational models of crowd human behavior. Verification and validation can then proceed with comparisons between outputs from simulations and behavioral data. The results of these preliminary efforts will initiate further work in the methods of incorporating human behavioral data into models and procedures for their validation.*

1. Introduction

The Department of Defense has strong programs in modeling and simulation (M&S) and relies heavily on M&S for analyses, prediction, and training for current and future operations. One scenario that has received a great deal of attention is simulation of crowd behavior, specifically in developing analytical tools that predict the response of individuals and crowds to non-lethal weapons. This interest has been spurred by current theaters of operation that are primarily peacekeeping and stability and support operations with frequent interactions between civilian non-combatants and small squads of Soldiers.

However, there is a universal recognition of the lack of real-life crowd data to provide guidance for these M&S efforts. Also lacking are methods to assess how well these M&S efforts relate to actual real life human behaviors (Zhou, et al 2010). Consequently, at best, these models are able to produce simulations that are theoretically based, visually realistic, and look probable to Subject Matter Experts (SMEs). However, the question becomes then what is actually modeled? Human behavior? Or merely a theoretical model of human behavior?

The Target Behavioral Response Laboratory's (TBRL) mission is to test the effectiveness of non-lethal weapons and systems, including crowd response to control force management with such weapons. Effectiveness of non-lethal weapons in crowd scenarios is assessed by evaluating how well the weapon controls the location and movements of the crowd members. This focus is based on the observation that Soldiers in crowd situations often issue commands controlling these behaviors such as “Stay Back!”, “Leave!” and the like.

In the past two years, the TBRL has collected behavioral, psychological, and sociometric crowd data on over 200 individuals in 14 crowd (7-19 persons) events under varied experimental manipulations. The basic paradigm is a rock throwing crowd facing a control force wielding a variety of simulated non-lethal weapons

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14. ABSTRACT
This paper describes the Army-funded exploratory work in progress at the Target Behavioral Response Laboratory. Crowd behavior data collected under controlled laboratory conditions form the basis for mathematical models of human behavior, which are then coded into computational models of crowd human behavior. Verification and validation can then proceed with comparisons between outputs from simulations and behavioral data. The results of these preliminary efforts will initiate further work in the methods of incorporating human behavioral data into models and procedures for their validation.

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(Mezzacappa, Cooke, & Yagrich, 2008; Cooke, et al, 2010). In addition, TBRL has recently successfully completed preliminary outdoor equipment testing with a crowd composed of 89 members.

Access to data on crowd-control force behavior has led the TBRL to develop a unique and innovative approach to M&S, where *data from behavior of real persons in tactically relevant scenarios* are the analytical link to the computational model. TBRL has received funding from an ARDEC In-house Laboratory Independent Research award to 1) develop and document methods and processes to generate computational models from mathematical models calculated from human behavioral data, and 2) to develop and document methods and processes to quantitatively verify and validate human behavioral models. The core task of the project is to *model the psychological forces that drive behavior as revealed by behavior*. The long-term goal of the study is to contribute to the creation of an M&S operational planning tool to provide commanders with the capability to predict crowd response to non-lethal weapon tactics, techniques, and procedures. A description of the project follows.

2. Method

2.1 The Conceptual Model: Lewinian Field Theory

2.1.1 The Life Space and Psychological Field

The crowd research program was developed under the theoretical framework of Lewinian Field Theory (Lewin, 1935, 1936). This metatheory states that behavior is a function of the person and of the person's environment, where the state of the person and that of the environment are not independent of each other.

To understand or to predict behavior, the person and the person's environment have to be considered as one constellation of interdependent factors. We call the totality of these factors the *life space* of that individual. The life space, therefore includes, both the person and his psychological environment. In Lewin's words then, "The task of explaining behavior then becomes identical with (1) finding scientific representation of the life space and (2) determining the function which links the behavior to the life space." Another way of conceptualizing these tasks relevant to the crowd situation is to identify the critical variables affecting people in the crowds and then to derive the equations linking the predictor variables to the outcome behavior. These equations then form the algorithm needed by M&S efforts.

2.1.2. Regions, Psychological Forces, Valences, and Locomotion

Central to field theoretical formulations of behavior are the concepts of regions of the life space and valanced psychological forces inducing locomotion to regions of the life space. If the region of the life space (which may represent an activity, a social position, an object or any other possible goal) is attractive to the person, it is said to have a positive valance, corresponding to a positive central field. If the region of the life space is repulsive to the person, it is said to have a negative valence, corresponding to a negative central field. The strength of the force toward or away from a region or goal depends upon the strength of that valence and the psychological distance between the person and the region or goal. The forces toward a positive or away from a negative valence can be called driving forces and they lead to locomotion.

Most behavior can be conceived of as a change of position – in other words, as locomotion (movement through a space) of the person toward a region of the life space. These movements can be psychological (thinking/believing he or she is closer to a goal) or physical (walking/running to an area).

What locomotions actually occur depends on the constellation of psychological forces. The construct force characterizes, for a given point of the field, the direction and strength of the tendency to change or locomote. The combination of a number of forces acting at the same point at a given time is called the resultant force. The relation between force and behavior can then be summed up in the following way: Whenever a resultant force (different from zero) exists, there is a locomotion in the direction of that force. The reverse also holds: whenever a locomotion exists, resultant forces exist in that direction. This relationship allows us to assess psychological forces empirically. That is, we can

use locomotions of persons as indicators of the psychological forces that are present in crowd-control team interactions with non-lethal weapons.

2.2 Empirical Methods

2.2.1. Overview of Methods

Using field theoretical approaches, the task at hand is to 1) identify the psychologically relevant forces within the crowd-control team scenario 2) determine the valence and strength of these forces. Based on the assumption that forces induce locomotion through the space, indices of these forces can be recorded through locomotions.

2.2.3 General Paradigm

The primary data recorded in the crowd-control force interaction were location and locomotion of persons during a task that simulated a crowd facing an area protected by a control force. The control force (one to three researchers functioned in this capacity) used either hand-to-hand combat weapons (foam batons) or stand-off projectile weapons (toy gun with foam projectiles) in interactions with the crowd (Mezzacappa, Cooke, & Yagrich 2008; Cooke et al, 2010).

The control force also had two different notional Rules of Engagement (ROE). Under the threat ROE, the control force actively tried to tag the crowd members in order to keep them away from the area. In the no-threat ROE the control force did not tag the crowd members but were allowed to move around the field to try to keep the crowd back simply by their presence. Tags ("target impacts") were indicated by blue chalk placed on the tips of the foam batons and the foam projectiles. In addition, baseline trials were included where there were no control forces present.

2.2.4 Induction of Psychological Forces

The crowd members were each given one beanbag. If the subject could get the beanbag into any of the targets at the far end of the field, behind the control force, then the group and/or individual was rewarded with points and money. This manipulation was intended to create a *positively valanced goal* at the target end of the field. The degree of attractiveness of this goal was manipulated by increasing or decreasing the amount of points or money that could be won. The control force, however, could tag the subjects on the way to the targets, which resulted in a loss of points and money for the group. Thus, the control force members represented a *negatively valanced goal* that was intended to create a repulsive force. The degree of repulsion was manipulated by increasing or decreasing the amount of points or money that could be lost by tagging. In summary, the scenario was designed to induce subjects to go towards targets and to go away from the control force.

Other sources of forces (constraints) were present on the testbed were the edges of the testbed. That is, during the experimental trials, crowd members were required to stay within the confines of the testbed, which was delineated, by physical objects and markers. Therefore, the edges of the testbed restrained locomotions to within the testbed. In addition, the presence of other persons on the testbed limited the locomotions of members (members were instructed to avoid collisions with others), thus also creating possible attractive, repulsive, or restraining forces on the testbed.

2.2.5 Motion Capture Methods

2.2.5.1 Recording

Again, based on Lewinian field theory, locomotions by the crowd member will reflect the psychological forces / valences that are present on the testbed. The goal is to assess these forces, through analysis of the direction and velocity of locomotions with respect to the sources of the forces (attractive forces toward the target, repulsive forces away from the control force).

The position and orientation data recorded by the Vicon MOCAP system can be described by three matrices: $X_{t,S}$, $Y_{t,S}$, $\theta_{t,S,}$ where t is the time step and S is an individual subject from a set of N total subjects. Three separate variables were used to describe the same information for the control force member(s): $\overline{X}_{t,C}$, $\overline{Y}_{t,C}$, $\overline{\theta}_{t,C}$, where C is the control force member (when multiple control forces are used).

In this study, the coordinate system of the raw data was defined with the origin in the center of the testbed and the positive Y-axis in the direction of the crowd's goal. Time zero for all trials was defined as the time when the first subject crossed the start line location. Thus, the x, y coordinates of the subject relative to the primary source of attractive forces (target) and relative to the primary source of repulsive forces (control force) is recorded for all individuals in the crowd. The primary dependent variable is the x, y coordinate location of the crowd member at any given time point during the trial with respect to the sources of attraction and repulsion.

Based on the Lewinian perspective, the magnitude of the attractive or repulsive force is reflected in these x, y coordinates and change over time of the x, y coordinates of the crowd members. More simply, the greater the attractive psychological force of the target the shorter the distance between an individual and the target at a given time point and the faster an individual will locomote toward the target. Similarly, the greater the repulsive psychological force of the target the longer the distance between an individual and the target at a given time point and the slower (including locomotions in the opposite direction) an individual will locomote toward the target. Thus, we can quantitatively assess the attractive and repulsive forces through examination of location and locomotion of crowd members, and then base computational modeling of these forces using these metrics.

2.2.5.2 Motion Capture Data Processing

These raw data are processed according to procedures detailed elsewhere (Cooke, et al 2010). Briefly, the initial steps that will be performed are the error checking (signal loss) and downsampling of the motion capture data. Raw x, y coordinate data are sampled at 120 samples per second. Prior procedures were to downsample to 30 samples per second by deleting all but data at time steps at set intervals (for example, 1st, 5th, 9th, etc.). Multiple data sets will be created by these methods with different non-overlapping intervals (for example 2nd, 6th, 10th etc. data set and 3rd, 7th, 11th, etc. dataset). Creation of these similar but separate data sets will allow us to conduct multiple exploratory and confirmatory regression analyses while avoiding capitalization on chance. Additional data sets may be needed for verification purpose.

2.2.6 Generating the Mathematical Model

2.2.6.1 Analytical Method

Model building within behavioral sciences is almost purely empirical and takes many stages. Regression analysis techniques, a statistical method of identifying a set of predictors for predicting a desired outcome will be performed. In the first stage, exploratory analyses are performed, where all information about all variables and subjects are entered and tested in for identification of those factors that show a reliable statistical relationship with the outcome of interest ($p < .2$).

In the second stage, confirmatory analyses are performed, using a new batch of data and using only those variables shown to have predictive power in the exploratory analyses. This regression analysis establishes strength of the relationship (weighted coefficients) between the predictor factor and the predicted outcome. The resulting regression model is then the mathematical expression that can be used to generate a computational model to predict an outcome (in this case, crowd member location and locomotion) based on a set of empirically-derived predictors. These predictors to be tested are detailed in the following sections.

2.2.6.2 Predictors Variables to be tested

2.2.6.2.1 Experimentally Manipulated Independent Variables

Each experimental day consisted of approximately 14-24 trials where subjects could approach the target for points while avoiding the control force and loss of points. Conditions on these trials were experimentally controlled and varied systematically (number of control force, type of weapon, ROE, etc.) Patterns of locomotion were expected to differ primarily depending on the type of weapon (hand-to-hand vs. stand-off) and the simulated ROE (threat vs. no threat) and number of control force. In previous analyses, we have demonstrated that these manipulated variables have statistically significant effects on crowd member behavior. Therefore, experimental conditions will be entered into the equation.

2.2.6.2.2 Covariates: Individual Psychological, Crowd Sociometric, and Demographic Variables

The importance of more ephemeral psychological and social variables in determining crowd behaviors has been widely recognized. While no attempt was made to manipulate directly these variables in the laboratory, they have been recorded as possible important covariates to be entered into the regression equation. In addition, demographic data on crowd members, such as age and gender and crowd-level information such as crowd size are also available for entry into regression analyses as possible important predictors of locomotion.

Data that mathematically capture psychological and social indices have been collected in the laboratory. Survey questionnaires using Likert (e.g., from 1-5) scales were used to mathematically capture psychological states throughout the experimental runs. Reliable and validated measures of anxiety (Spielberger, 1983), as well as custom-constructed questionnaires about feelings, plans, expectations were collected throughout the study. Standard procedures for questionnaire and survey administration were followed in these data collections.

In addition, novel crowd-level social metrics were recorded and derived on three different measures using Social Network Analysis methods (Carrington, Scott, & Wasserman, 2005; Wasserman & Faust, 1994). First, individuals indicated who in the crowd they knew before coming to the experiment (at times siblings, families, or roommates participated together). In addition, videotapes of the crowd member interactions during the experiment were coded to analyze communication among crowd members. Finally, at the conclusion of the study, members were asked to identify who they believed acted as a leader during the experiment. These data are then processed to yield a number of crowd sociometric measures. These quantitative measures of psychological and social states can then be entered into regression analyses predicting locomotion behavior.

2.2.6.2.3 Assumptions

Again, this effort differs from previous work in that we are measuring fields of forces under controlled laboratory conditions, then recreating these fields of forces within the virtual environment. For these initial attempts, several assumptions and constraints are made. We are assuming linear relationships among the variables. While there may be important interaction effects among the predictor variables, we will be focusing on and testing main effects of the predictor variables. For analyses of effects of the control force, we will constrain the model to considerations of one control force person whose location is considered as mathematically fixed for the purposes of these analyses. We are also assuming that the control force person is a homogenous point, whereas, data from our laboratory indicate that the repulsive force is stronger in front of the control force person compared with his back, and on the right side (where the weapon is held) compared with his left. We are also assuming the crowd member is a homogenous point without behavioral differences in orientation (front and back of head). Finally, we are only considering the approach of the crowd toward the targets, not the return to the start line base after throwing the beanbag. These are initial exploratory efforts; we hope to set the foundation for development of more complex higher-fidelity models.

2.2.6.2.4 Vector Regression Analyses

The x, y location data will be submitted to vector regression analyses, predicting direction and speed of movement at a given time step from predictor variables (i.e., arising from experimental manipulations, individual psychological, crowd sociometric, and demographic factors). Four separate vector regressions will be performed, corresponding to each of the primary sources of attraction and repulsion in the testbed—target, control force, sides of the testbed, and other crowd member (where influence of other persons in the crowd will be conceptualized as distance to nearest person, next nearest person, etc).

In the first exploratory analyses stage, as many variables as possible will be entered into the equation, including location relative to source (e.g., location relative to the target in the target vector regression equation; location relative to the control force in the control force regression equation), experimental manipulations, individual psychological, crowd sociometric, and demographic variables. In addition, each person's subject code number will be entered to

test for the importance of inter-individual differences. Standard analytic strategies (Cohen & Cohen, 1983) will then be used including hierarchical and/or stepwise regression for identification and downselection of predictors for each of the four equations based on relative size of coefficients derived for each.

After specification of the final equations for each of the sources, a final confirmatory vector regression analysis will be performed using a new set of motion capture data (derived from the initial downsampling of the raw motion capture files). The set of vector regression equations with identified predictor variables and associated coefficients will be computed. This set of equations will be used to predict crowd movement in response to control force with non-lethal weapons. That is, the final set of confirmatory vector regression equations (mathematical model) will be used as the computational model.

2.2.7 Analyses of Simulation Output

2.2.7.1 Running the computational model

Up to this point, we have outlined the processes underway to generate a computational of crowd locomotion from data. That is, the final product of the work is a set of data-derived algorithms derived from data that describe a person's locomotion through the testbed in the crowd-control force scenario in this laboratory. These data-derived algorithms, which already incorporate psychological and social factors, can then be used as a computational model of human crowd locomotion behavior. As with any computer model, data from an initial state (location on testbed) of each crowd member is submitted to processing at the first step. Calculations resulting from each of the four vector regression equations will result in a vector indicating the speed and direction of the crowd member for the next time step. These four vectors will be summed to derive a final resultant vector for that individual for that time step. The iterations continue through to the end of approach to the scenario.

2.2.7.2 Inputting Control Force Behavior

As the rationale of the computer program is to predict the crowd response to control force, the critical input is the behavior of the control force. For verification and validation purposes, the same control force rules of engagement used in the laboratory will be inputted. In this way, the crowd simulation will be responding to control force behavior that is similar to that performed in the laboratory.

2.2.7.2 Required outputs from the model

Just as model building based on data requires mathematical capture of the behavior of real humans, computer model verification and validation requires mathematical capture of the behavior of virtual agents. More specifically, what is needed is the exact same data that is recorded for the humans in the laboratory- x, y coordinate data on the location of each of the agents relative to sources of attraction, repulsion, or restraint.

2.2.7.3 Comparators

A one-to-one comparison between data from each human to each virtual agent is possible but time-intensive and cumbersome. A comparison of crowd level aggregate measures between those derived from data recorded in the laboratory and those derived from data outputted by the simulation is more realistic and more in keeping with the real life use of the model. That is, a commander trying to predict crowd response is not as concerned about who in particular breaches the line in the sand, as whether a breach is attempted by any crowd member at all.

Using data derived from individual measures, we have derived several aggregate and systemic crowd level measures (Cooke, et al, 2010). The geometric center of the crowd is the central point of the area the crowd occupies. In contrast, the centroid of the crowd is the central tendency of all members of the crowd, the average location. Dispersion, a measure of the spread of the group was derived from the average radii of the individuals of the group.

The leading edge and trailing edge are the front and back of the crowd respectively. The leading and trailing edge are defined by the individual crowd member who was farthest to the front or

rear along the axis of approach. Likewise, the closest distance between any individual and the closest control force member is easily calculated for each time step. The leading edge of the group tracked over time (possibly corresponding to an individual breaching the line in the sand), proved to be especially useful in previous analyses (Cooke, et al, 2010).

Approximations of the model's fit can then be derived by comparison of the quantitative aggregate crowd measures calculated from the model output versus those collected in laboratory. That is, how well the computer model simulates the behavior of real people can be indexed by comparing leading edge, centroid, dispersion, and streamline measures derived from the model with those from the laboratory crowd. How these comparator processes can be used to perform model verification and model validation is outlined below.

2.2.7.4 Model Verification

One aspect of model verification can be performed by running the simulation under the same conditions and parameters as the laboratory conditions that produced the data on which the model was built. That is, if the computational model was generated based on behavioral data produced in a laboratory under a set of conditions, inputting these exact conditions should result in similar crowd behavior response. In other words, if the mathematical model is properly constructed, the computed output should match the laboratory data that generated the computational model.

2.2.7.5 Model Validation

A computational model is most useful when it can predict crowd response to novel situations or to a set of novel conditions. Such a model is said to have predictive validity. Predictive validity can be established if the outputs from the computational model are similar to laboratory data collected under conditions different from those on which the model was based. For example, as stated above, in computing the vector regression equation, we used data arising from conditions where only one control force person was present. We do have; however, data on crowd behavioral response when two and three control force persons are present. Predictive validity can be established if the output from the computational model set to simulate three control force personnel is similar to the crowd behavioral data collected in the laboratory in response to three control force personnel.

3. The Way Forward

Critical to future efforts is attention to a novel sort of interoperability. That is, these efforts highlight the necessity that laboratory investigators and model creators have a common conceptual scheme or framework on which to capture and analyze behavior. In general, there needs to be interoperability between the data and processes in the laboratory experiment and the data and processes for the computer model. It is hoped that future efforts would result in interoperability between physical laboratory and environmental simulations, such that a computer modeler could build scenario to match the experiment conditions in laboratory (on weapon, control force, crowd, or environmental characteristics) or vice versa. Ideally, though, there should be developments in methods to capture data on human crowd behaviors in theater under real control force management with non-lethal weapons in real-time.

In addition, the findings of this project extend to other scenarios and behaviors. While we have focused on Lewinian Field Theory in the prediction of locomotion, the approach is broadly articulated to be useful in predicting behaviors other than those of locomotion (Lewin 1935, 1936), thus would assist in modeling of other behaviors and other operational scenarios in the future.

Model fidelity will be increased in future efforts. Initially, we have constrained our model in numerous ways; future work will address how to incorporate other important variables such as orientation of head of crowd member, relative orientation of control force and weapon, and discrete events, such as communications, weapon hits and misses, and different modalities of non-lethal weapon stimuli. We have used regression analyses in these initial efforts. In the future, more complex mathematical and statistical methods of data capture such as Structural Equation Modeling and associated Goodness- of-

Fit measures can be explored for their utility in guiding generation of computational models.

To conclude, these methods provide guidance on the generation of computational models from human behavioral data, and verification and validation of models against human behavior. More broadly, the proposed methods set the stage for development of standards for data incorporation into computer models of human behavior and set the stage for development of standards for validation of human behavior models by data.

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